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THE EFFECT OF ADDING MAGNESIUM TO THE FILLER MATERIAL ON THE TENSILE PROPERTIES OF TIG WELDED AA 6082 ALUMINIUM ALLOY

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Original Article

ABSTRACT

Aluminium 6082 is a moderate strength alloy with good weldability. Tungsten inert gas (TIG) welding is the most common welding process of this alloy. AA6082 is one of the major alloys used in automotive, shipbuilding, aircraft and structural applications. Tensile strength of welded joints is an important design parameter when it is used for these applications. ER 4043, which contains 5% silicon as major alloying element and ER5356, which contains 5% magnesium as major alloying element, are the most common filler materials used for the welding of AA6082 alloys. In the present investigation, magnesium is added to silicon-based ER 4043 filler wire at different percentage levels, and this new filler wire with altered chemical composition is used for welding of 6082 aluminium plates. The effect of adding magnesium to the filler wire is investigated by using design of experiments. From experiments it is found that this new filler wire is capable of providing higher tensile strength for the welded joint. It is found that the increase in the tensile strength is due to the formation of magnesium silicide intermetallic phase in the weld zone. The presence of various intermetallic phases are identified by microstructural analysis. The amount of magnesium content in the new filler wire which will give the maximum tensile strength to the joint is optimized by using factorial design, artificial neural network and genetic algorithm.

***KEYWORDS:** Aluminium 6082, Filler Wire, Mechanical properties, Microstructure, TIG Welding, Intermetallic Phase, Magnesium Silicide & Artificial Neural Network*

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1. INTRODUCTION

Aluminium 6082 is one of the most widely used Aluminium alloys for automotive, shipbuilding, aircraft and structural applications [1]. Magnesium and silicone are the key alloying elements in 6082 aluminium alloys. Aluminium and its alloys are gaining popularity in recent times due to their excellent corrosion resistance, moderate strength, light weight and ease of fabrication. In the automobile field, the acceptability and usage of aluminium alloys have been increased drastically due to their light weight which can impart higher fuel economy [2]. Weldability of aluminium alloys is a key mechanical property that has a vital role in the selection of these materials for various applications [3]. Due to the increasing demand of material with light weight and significant strength has resulted in paying more attention and conducting depth research for developing better welding techniques for these materials [4].

Tungsten inert gas (TIG) welding is an arc-welding process used for joining of two work piece material by heating them with an electric arc established between a non-consumable electrode and the work piece material [5].

It is the most recommended welding method for joining of aluminum and its alloys [6–9]. ER 4043, which contains 5% silicon, ER 4047, which contains 11% silicon and ER5356, which contains 5% magnesium are the most common filler materials used for the welding of 6000 series aluminium alloys. TIG welding using ER5356 filler yields more strength and hardness compared to ER4043 and ER4047 [10, 11]. Shah et al. investigated the effect of a filler wire on the mechanical properties of TIG welded AA6061 alloy. They found that those samples welded with ER4043 filler wire have higher Vickers hardness and corrosion resistance compared to samples welded with ER4047 filler wire [12]. ER 4043 filler material is capable of providing good ductility to the welded joint due to the presence of silicon and hence the chance of crack formation in the weld zone is less [13]. But the strength of the welded joint is poor as there is no Mg_2Si intermetallic phase in the weld metal [14]. It has been found that the use of filler wires with higher Mg and Mn content leads to a significant reduction in porosity [15]. Aluminium 6082 alloy welded with ER 5356 filler wires is prone to crack formation during the solidification of molten weld pool [16]. The aluminium alloy welded with magnesium rich filler wire is subjected to corrosion also.

The chemical composition of filler wire is an important parameter that decides the mechanical properties of the welded joint. A large number of intermetallic particles are formed during the solidification of the aluminium alloy. The major intermetallic phases present in the 6000 series of aluminium alloys are identified as α-Al_5FeSi, β-$Al_{15}(FeMn)_3Si$, Al_9Mn_3Si, α-$Al_{12}Fe_3Si$, Mg_2Si. Presence of these intermetallic phases in the solid solution has a substantial influence on the mechanical properties of these alloys [17]. Among these intermetallic phases the Mg_2Si precipitates formed by the combination of magnesium (Mg) and silicon (Si) are capable of providing strength and hardness to the aluminium alloy [18]. These precipitates occur in several forms, which may be divided into the following three categories; first category is the smallest type of β" Mg_2Si precipitate. These rod-shaped β" Mg_2Si precipitates contributes most to mechanical properties when densely dispersed. Second category is the larger version of rod-shaped precipitate β' Mg_2Si, that grows from the β" category. The β' precipitates have a negligible contribution to mechanical properties. Third category is β Mg_2Si which is the largest Mg_2Si precipitates. These precipitates are cube-like in shape and due to its size it contributes nothing to the mechanical properties [19–24].

Inferior weld strength, reduced ductility of the weld metal and heat effected zone, poor corrosion resistance, crack formation are some key issues in the welding of 6082 aluminium alloy. These issues can be addressed by properly changing the chemical composition of filler material. The improved mechanical properties of the welded joint can make this alloy more suitable for automobile, aviation, aerospace, rail cars, and marine industries. The use of light weight alloy with high specific strength would result in weight reduction in automobiles, rail cars, etc., with increasing fuel efficiency and reducing environmental pollution. So far, no research is carried out for investigating the effect of changing chemical composition of above filler wires on the mechanical properties of welded joints. The objective of the research is to study the effect of adding magnesium to ER 4043 filler material on microstructure and mechanical properties of TIG welded AA6082 aluminium alloy. In the present investigation magnesium is added to silicon based 4043 filler material at different percentage levels and the magnesium added filler wires are used for TIG welding of 6082 aluminium alloy plate.

2. EXPERIMENTAL WORK

2.1 Materials and Method

The material used for this investigation was AA6082 aluminium plate of 6 mm thick. The chemical composition of the aluminium alloy was obtained by spark optical emission spectrometry. In this test spark was generated between a metal

sample and an electrode by applying electrical energy. The generated spectrum was analyzed for detecting the quantitative and qualitative analysis of the sample. The chemical composition of the base metal and different types of filler material used in this investigation are given in table 1. Aluminium plates of dimension 125 × 100 × 6 mm thick were used for this investigation. The plates were machined to obtain V groove having an angle of 60° and root face was kept at 2 mm. Edge preparations were done with standard groove angle and root gap as given in the figure 1.

Table 1: Chemical Composition

Material	Mg	Si	Fe	Mn	Cr	Cu	Ti	Zn	Sn	V	Be	Others	Al
AA 6082	0.87	0.95	0.15	0.77	0.02	0.02	0.01	0.08	0.01	0.02	----	-----	Balance
ER 4043	0.01	4.5-6	0.80	0.05	-----	0.30	0.20	0.10	---	---	0.0008	0.05	Balance
ER 4043+1.5%mg	1.50	4.5-6	0.80	0.05	-----	0.30	0.20	0.10	---	---	0.0008	0.05	Balance
ER 4043+3%mg	3.00	4.5-6	0.80	0.05	-----	0.30	0.20	0.10	---	---	0.0008	0.05	Balance
ER 4043+4.5%mg	4.50	4.5-6	0.80	0.05	-----	0.30	0.20	0.10	---	---	0.0008	0.05	Balance

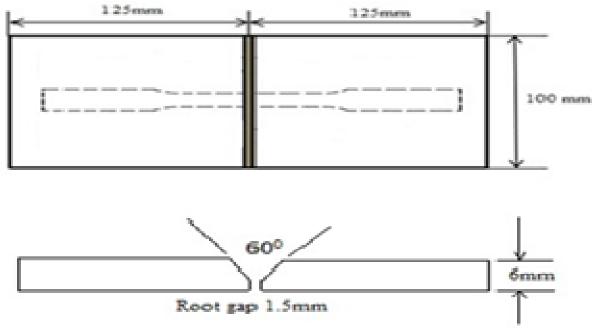


Figure 1: Weld Specimen.

ER 4043 filler wires after adding magnesium at different percentage levels were used for welding. Magnesium was added to the ER 4043 filler material by melting ER 4043 filler wire in an electric metal-melting furnace. Care had been taken by supplying inert gas argon on the surface of motel metal to prevent the oxidation of magnesium. The molten material was poured into a boron silica glass tube with 4 mm inner diameter and 200 mm in length. By using this casting process, different filler wires were made with varying percentage of magnesium content. The presence of magnesium in the new filler wire was obtained by chemical analysis. The filler wires made by the casting process are shown in figure 2.

2.2 Selections of Process Variables

The key process variables that influence the tensile strength of the welded joint were identified. From various studies conducted earlier the effect of arc voltage and torch angle are found less significant [25–28], and therefore not considered in this study. Since, special filler wires prepared by adding magnesium to ER 4043 filler wire were used in this study, manual TIG welding method was used to overcome the compatibility issues of automatic filler wire feeding mechanism. The proper welding speed which will give good bead geometry and good penetration is identified from trial run. Welding speed is maintained at a constant value of 100 mm/min by hand control of a skilled welder. Welding current, gas flow rate and chemical composition of the filler wire were selected as key process parameters.

2.3 Levels of Identified Parameters

The feasible working range of different process parameters was identified by carrying out trial welding experiments on AA 6082 aluminium alloy plate of 6 mm thickness. All types of filler wire manufactured by casting were used in the trial run with different combinations of process parameters. From the above trial run, the maximum and minimum levels of each

factor were determined, and the working ranges of the different process parameters identified are given in Table 2. Only three levels are selected for current and gas flow rate in order to minimize the number of experiment trials. The maximum percentage of magnesium in the filler wire is limited to 4.5%, which is near to the range of silicon in the 4043 filler wire.

Table 2: Levels of the Process Parameters

Factor	Units	Level 1	Level 2	Level 3	Level4
Current(A)	A	190	210	230	---
Gas flow rate	L/Min	13	14	15	---
Mg Content	%	0	1.5	3.0	4.5

Figure 2: Magnesium Added Cast Filler Wire.

2.4 Design of Experiment

The design of experiment is a systematic procedure used to investigate the effect of various input parameters that have influence on the output of a process [29]. Design of experiment method is used for screening the significant factors that influence the response parameter. It can also be used as a model to improve the output of a process. Factorial design is primarily used for screening the significant factors in a process that influences the response variable. It can be sequentially used for model and refine a process. By this method, it is also possible to study the effect of interaction of input parameters on the output variable. Factorial designs are classified as full factorial design and fractional factorial design. In the present investigation full factorial design is used for optimization. The matrix designed based on factorial design approach orthogonal array is given in table III.

2.5 Experimental Procedure

TIG welding is performed by selecting the values of the process parameters as per the design matrix. The welding experiments were carried out from Welding Research Institute - BHEL - Trichy by using Lincoln make TIG weling machine. Before welding, the work piece materials were pickled with a solution of NaOH and HNO_3 to remove the stains and contaminations. The work pieces were wire-brushed to remove oxide film and also degreased with acetone. The work pieces were fixed on the steel backing plate and clamped to it to maintain the uniform root gap and alignment (Figure 3). Manual welding is completed in two passes. Thirty six welded specimens were prepared as per the process parameters in the design of experiments. Some of the specimens welded were shown in the Figure 4. Specimens for tensile test were taken from welded plate in the area of sound weld. The specimens were machined as per ASTM E8 M standards. The

dimension of the test specimen was shown in Figure 5. Tensile testing of all the specimens were performed by using computerized universal testing machine, and the results are tabulated in Table 3. It was noticed that all the welded specimens were failed in the weld region. Therefore, ultimate tensile strength obtained from the tensile tests can be taken as the strength of the welded joint. A few samples of the fractured tensile test specimens were given in figure 6.

Figure 3: TIG Welding.

Figure 4: Welded Specimens.

2.6 Analysis of Variance

Analysis of variance (ANOVA) is a statistical method used to evaluate the differences among group means in a sample observation. It gives a clear picture of the extent to which the process parameter affects the response, and the level of significance of each factor under consideration. It uses sum of squares, and the F statistics to calculate the relative importance of different parameters involved in the process. It can also give information about measurement errors and uncontrolled parameters associated with an experiment. The adequacy of the model in experimentation can be checked with ANOVA with the help of F statistics. If the calculated value of F ratio is higher than the tabulated value of F-ratio, then it is confirmed that the developed model is satisfactory for representing the relationship between the response parameter and control factors at a desired level of significance. ANOVA was calculated by using Minitab 18 software. The results are shown in Table 4. The higher F value implies that the corresponding term makes a significant contribution to the response. The percentage contribution of different parameters was determined by calculating ratio of sum of squares corresponding to that parameter to the total sum of squares. The mathematical model obtained showing the relationship between the selected welding parameters and the ultimate tensile strength of the joint is shown below.

$$UTS = -594+7.06\ CURRENT-7.85\ \%\ Mg-0.01669\ CURRENT*CURRENT+11.28\ \%\ Mg*\%\ Mg-\ 2.076\ \%\ Mg*\%\ Mg*\%\ Mg$$

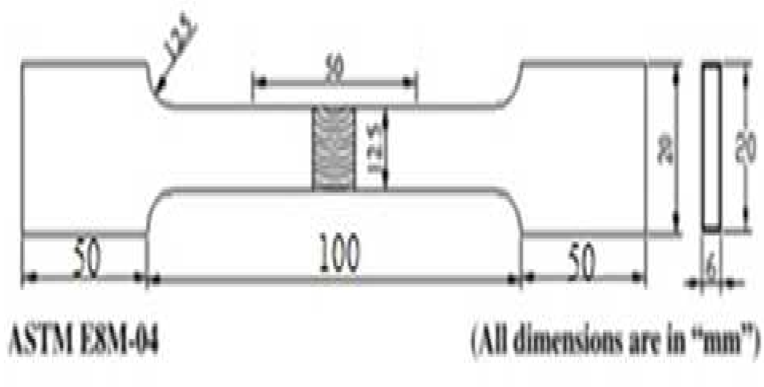


Figure 5: Dimension of Tensile Test Specimen.

Figure 6: Tensile Test Specimens.

Table 3: Design Matrix –Factorial Design

Std Order	Run Order	Level of Factor			Tensile Strength (MPa)
		Current (A)	Gas Flow Rate (L/Min)	Mg (%)	
6	1	190	14	1.5	158.10
24	2	210	15	4.5	150.15
16	3	210	13	4.5	155.05
27	4	230	13	3.0	165.03
35	5	230	15	3.0	169.07
1	6	190	13	0.0	150.11
18	7	210	14	1.5	168.16
28	8	230	13	4.5	153.96
9	9	190	15	0.0	148.12
32	10	230	14	4.5	155.18
22	11	210	15	1.5	157.92
8	12	190	14	4.5	145.13
17	13	210	14	0.0	147.92
36	14	230	15	4.5	150.15
7	15	190	14	3.0	162.88
20	16	210	14	4.5	160.07
25	17	230	13	0.0	141.87
34	18	230	15	1.5	152.11
23	19	210	15	3.0	179.75
10	20	190	15	1.5	150.20
12	21	190	15	4.5	145.04

Table 3: Contd.,

11	22	190	15	3.0	164.02
26	23	230	13	1.5	148.21
13	24	210	13	0.0	155.13
29	25	230	14	0.0	149.71
15	26	210	13	3.0	169.30
2	27	190	13	1.5	148.10
14	28	210	13	1.5	150.27
31	29	230	14	3.0	170.41
33	30	230	15	0.0	145.33
4	31	190	13	4.5	155.18
21	32	210	15	0.0	155.20
19	33	210	14	3.0	180.31
30	34	230	14	1.5	159.88
3	35	190	13	3.0	170.44
5	36	190	14	0.0	140.02

Table 4: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	17	3412.5	200.74	20.86	0.000
Linear	7	2931.3	418.77	43.52	0.000
CURRENT	2	379.6	189.82	19.73	0.000
GAS FLOW. R	2	61.0	30.50	3.17	0.066
% Mg	3	2490.7	830.25	86.28	0.000
2-Way Interactions	10	481.2	48.12	5.00	0.002
Current*Gas Flow Rate	4	167.2	41.79	4.34	0.012
GAS FLOW RATE*% Mg	6	314.0	52.34	5.44	0.002
Error	18	173.2	9.62		
Total	**35**	**3585.7**			

3. RESULTS AND DISCUSSIONS

The effect of adding magnesium to the silicon rich filler wire is investigated by using full factorial design of experiment method. From the ANOVA, it is found that adding magnesium to the filler wire has a significant role in the tensile strength of the welded joint. From ANOVA it is clear that adding magnesium to the ER4043 filler wire substantially increases the tensile strength of the welded joint. It is observed that 3% of magnesium addition gives the maximum tensile strength to the joint. Based on ANOVA the contribution of the each parameters are calculated and it is found out that magnesium content in the filler wire is the most significant parameter that influences the tensile strength of the joint with 69.4% contribution. The p value of less than 0.05 strongly supports the rejection of the null hypothesis. The percentage of contribution for current is found to be 10.6%. The contribution of current is comparatively low here because the range of value of current is selected in such a way that it would result a sound weld. Current value below 190 A is not considered in this experiment because it will result in lack of fusion due to insufficient heat input. Similarly, current value above 230 A also not considered because it will result in burning of base metal due to excess heat input. So, both low and high values of current will result in reduced strength of the joint. Gas flow rate is not a significant parameter and the contribution of the same is limited to 1.7%. But two-way interactions of current and gas flow rate have some significance with 4.6% contribution. Similarly, the interaction of gas flow rate and magnesium content in the filler wire has some more significance with a contribution of 8.8%. The details are given in the Table 5.

Table 5: Influence of Process Parameter-New Filler Wire

Sl. No	Parameter	Type of Interaction of parameters	Percentage of Contribution
1	Magnesium content in the filler wire	Linear	69.4
2	Current	Linear	10.6
3	Gas flow rate	Linear	1.7
4	Current*Gas flow rate	Two way	4.6
5	Current*% Mg	Two way	----
6	Gas flow rate*% Mg	Two way	8.8
7	Error		4.9

3.1 Microstructure and Intermetallic Phase

The microstructural changes occurring in the weld metal by adding magnesium in the filler wire were studied by using microstructure obtained by SEM and optical microscope. Specimens were sectioned by using abrasive cut-off wheels, ground and polished as per the standard metallographic procedures. For revealing more microstructural features, the specimens were etched using Kellers reagent (1 ml HF, 1.5 ml HCL, 2.5 ml HNO_3 and 95 ml H_2O). The microstructures of the weld metal were captured with the help of an image analyzing software coupled with an optical microscope at a magnification of 400X. The microstructures were obtained by taking specimens from work piece welded with filler wires of different magnesium content. The microstructure of the specimens welded with filler wires of different magnesium content are given in Figures 7–10. The microstructure of the joint welded with ER 4043 i.e. wire containing no magnesium content resulting in a coarse grain structure is shown in figure 7. The mean tensile strength observed is low in this case. The coarse grain structure is responsible for the comparatively poor strength of the joint. Small traces Mg_2Si can be seen as dark spots in the microstructure of the metal welded with 1.5% of magnesium in the filler wire (Figure 8). The presence of Mg_2Si occupied in the inter granular space is more visible in the microstructure of the welded joint made with filler wire of 3% of magnesium content as shown in figure 9. An addition of magnesium by 4.5% further intensifies the formation of Mg_2Si in inter granular space (Figure 10). Upto a certain range the presence of Mg_2Si is useful for grain refinement but excess quantity of Mg_2Si weakens the strength.

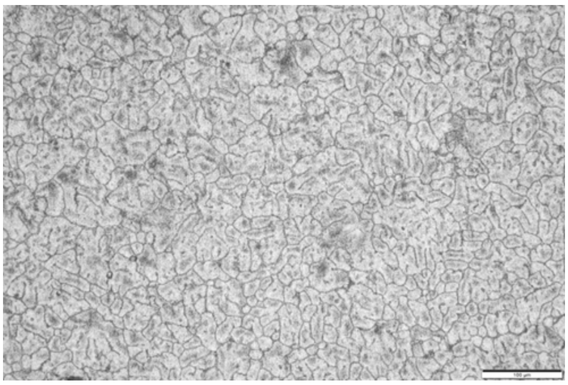


Figure 7: Microstructure of Weld Metal with 0% Mg Added Filler Wire in as Welded Condition.

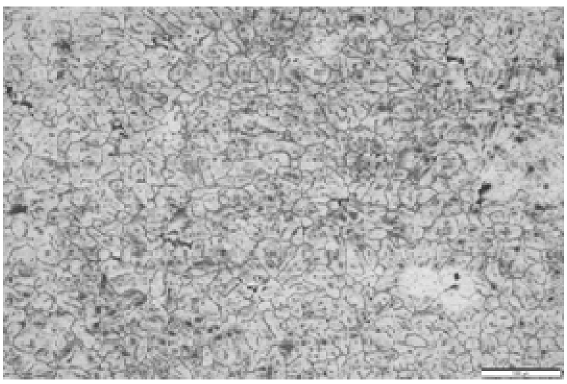


Figure 8: Microstructure of Weld Metal with 1.5 % Mg Added Filler Wire in as Welded Condition.

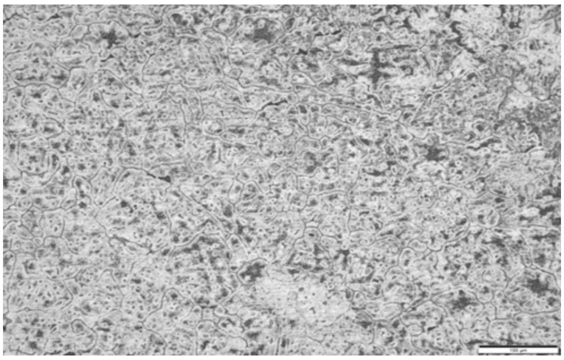


Figure 9: Microstructure of Weld Metal with 3 % Mg Added Filler Wire in as Welded Condition.

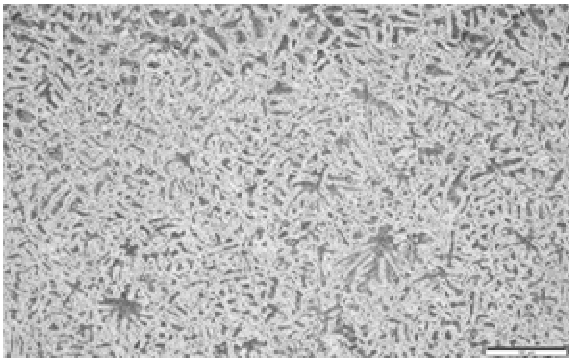


Figure 10: Microstructure of Weld Metal with 4.5% Mg Added Filler Wire in as welded Condition.

SEM microstructures of the specimen welded with ER 4043+ 3% Mg are shown in Figures 11 and 12. The chemical composition of the weld metal was identified by Energy dispersive X-ray spectroscopy (EDXA) incorporated with scanning electron microscope.

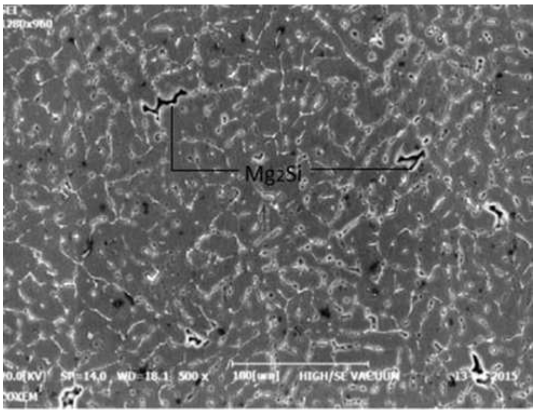


Figure 11: SEM Image- ER 4043+ 3% Mg.

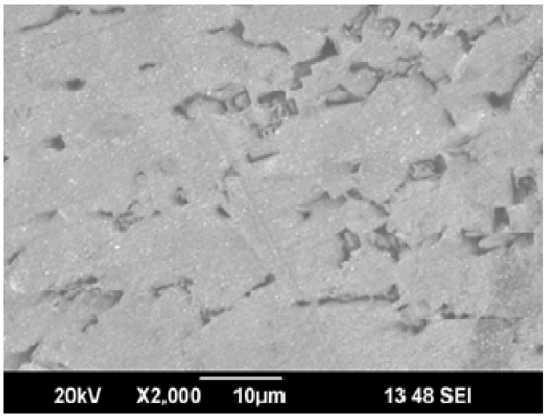


Figure 12: SEM Image- ER 4043 + 3% Mg.

The EDXA of the specimen welded with ER 4043+ 3% Mg content is shown in Figure 13. The EDXA confirms the presence of both magnesium and silicon in the weld zone. SEM microstructures of the specimen welded with ER 4043+ 0% Mg is shown in Figure 14. The EDXA of the same specimen is shown in the Figure 15 and it confirms the presence of silicon in the weld zone but no magnesium. The XRD analysis was performed to identify the composition of intermetallic compounds in the weld metal. The XRD spectra confirmed the presence of following intermetallic phases in the weld metal. These intermetallic phases are Al_5FeSi, $Al_{15}(FeMn)_3Si$, Al_9Mn_3Si, $Al_{12}Fe_3Si$, Mg_2Si (Figure16). These intermetallic phases have various shapes of particles such as needle-like, plate-like, polygonal and “Chinese script”. In the aluminium 6000 group of alloys, the intermetallic phases formed during solidification imparts the strength to these alloys [30]. From previous investigations and literature it has been found that the formation of β″(Mg2Si) phase and precipitation of intermetallic phases containing Si, Fe and Mn play a significant role in the superior mechanical properties of these alloys [29,30]. The amount of strengthening depends on the extent of β″ precipitation during the solidification, and with an increase of Mg content in the filler wire, the β″(Mg2Si) precipitation increases [31-35]. In terms of size and distribution, it can be located at the grain boundaries and may form a dendritic network structure. The presence of various intermetallic phases can improve the strength of the fusion zone by a mechanism called precipitation strengthening effect [31-35]. The presence of Mg_2Si can improve micro-hardness and hard intermetallic compounds can improve the mechanical properties of the fusion zone [36-39]. The surface plot shows that as the magnesium content in the filler wire increases the tensile

strength of the joint and maximum value is obtained at around 3% of magnesium. The optimum value of current is 215 A for maximum strength. The variation of tensile strength with current and magnesium content is given in the surface plot (Figure 17). The variation of the ultimate tensile strength of the welded joint with current and magnesium content in the filler wire is shown in the contour plot given in Figure 18. From the above plot it is evident that magnesium content above 3% can substantially improve the strength of the joint. The main effect plots are shown in the Figure 19. It is clear that by adding magnesium in the 4047 filler wire tensile strength of the joint can be improved. SEM microstructure study shows clearly the presence of Mg_2Si as dark spots.

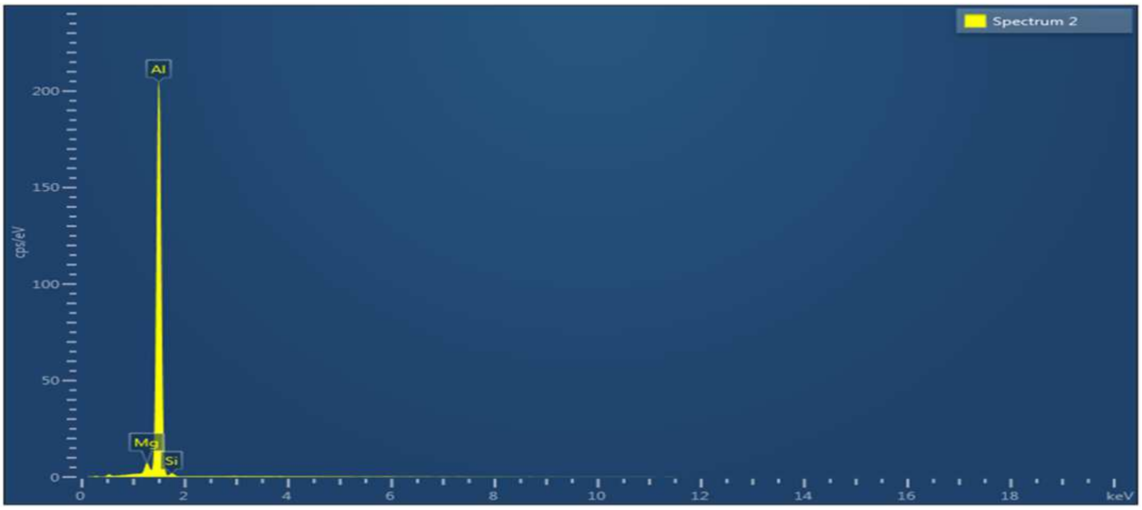


Figure 13: EDXA spectra- ER 4043+ 3% M.

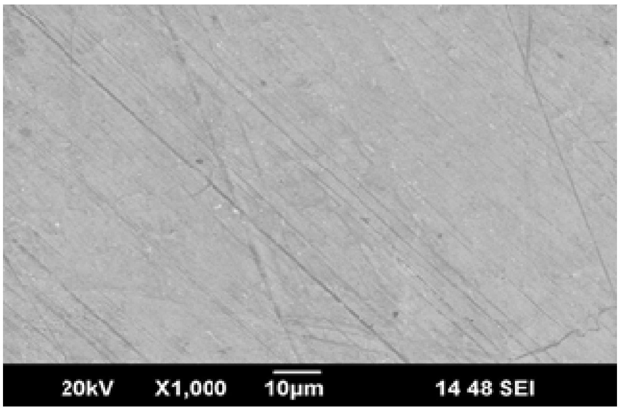
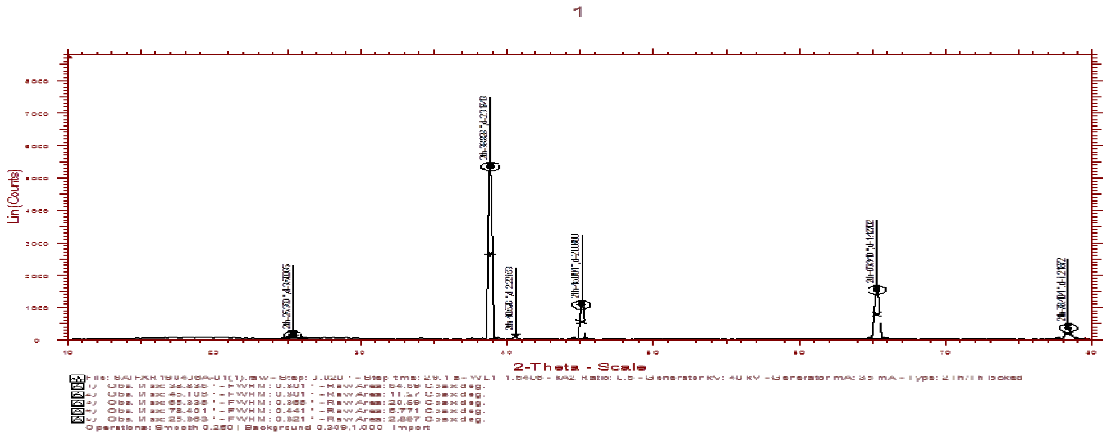


Figure 14: SEM Image ER 4043-No Mg Content.

The formation of intermetallic particles of Mg_2Si along the grain boundary of the alloy is responsible for the improvement in the strength of the joint. The variation of tensile strength with magnesium content in the filler fire, current and gas flow rate are given in figures 20–22. The mean tensile strength for the magnesium content of 3% is obtained as 170.13MPa. Similarly, the mean tensile strength is obtained maximum at a current of 210 A and a gas flow rate of 14 L/min.

Figure 15: EDXA Spectra- ER 4043-No- Mg Content.



1. $Al_{15}(FeMn)_3Si$ 2. Al_9Mn_3Si 3. Mg_2Si 4. Al_5FeSi 5. $Al_{12}Fe_3Si$

Figure 16: XRD Spectra.

3.2 Optimization of Process Parameters

Genetic algorithm is a useful tool for optimization of process parameters [37]. The optimum percentage of magnesium content in the filler wire was found out by using artificial neural network (ANN) and genetic algorithm. A fitting function which gives the relationship between tensile strength and the process parameters under consideration was generated by using ANN. The optimum values of the process parameters for maximum tensile strength were obtained by using the fitting function generated in Genetic Algorithm. The screen shot of the optimization tool which shows the optimum values of the process parameters are shown in figure 23.

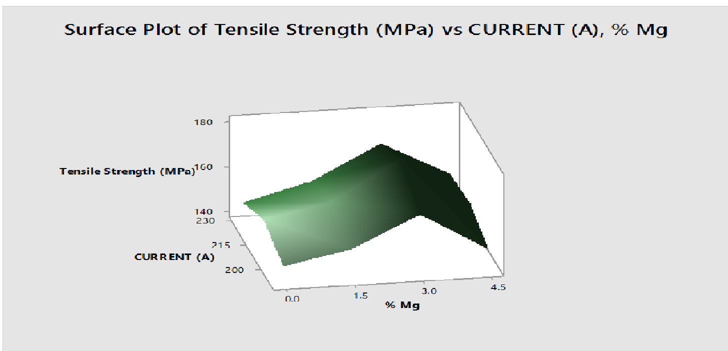


Figure 17: Surface Plot.

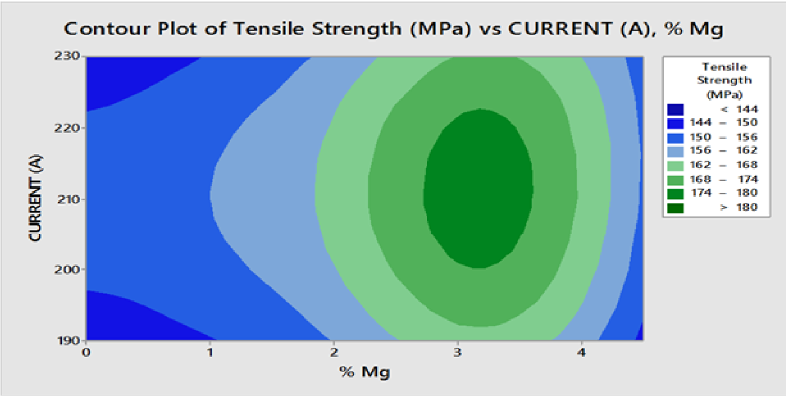


Figure 18: Contour Plot.

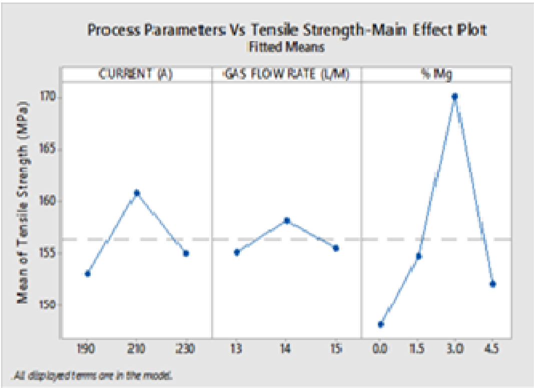


Figure 19: Main Effect Plot.

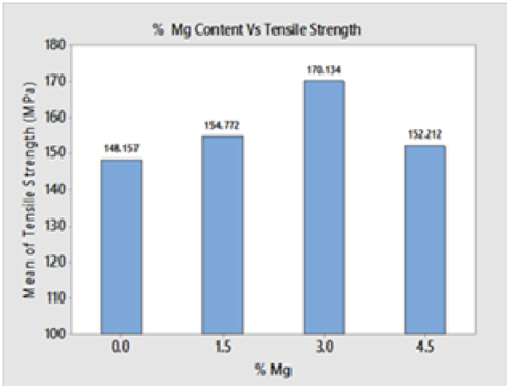


Figure 20: Mg content Vs Tensile Strength.

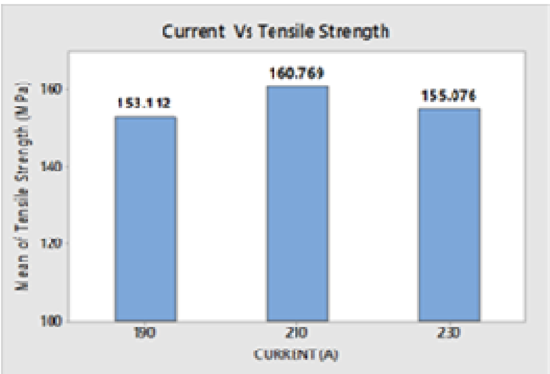


Figure 21: Current Vs Tensile Strength.

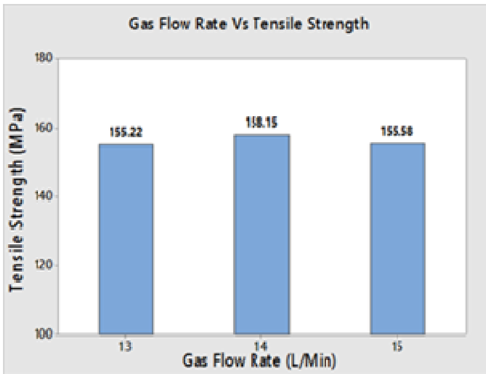


Figure 22: Gas Flow Rate Vs Tensile Strength.

3.3 Confirmation Test

For comparing the ultimate tensile strength as predicted by the model with the experimental value, a confirmation test was conducted by selecting the optimum welding parameters. The optimum welding parameters obtained were 210.93 A current, 13.707 L/min gas flow rate and 2.71% magnesium content in the filler wire. Three samples were welded by selecting the above parameters and the tensile tests were carried out for these specimens. The results were tabulated in Table 6.

Table 6: Confirmation Test

Optimum Process Parameters			UTS Predicted by Model (MPa)	UTS Experimental (MPa)
Current(A)	Gas Flow RateL/Min	% Mg		
210.93	13.707	2.71	174.49	173.55
				174.61
				174.22

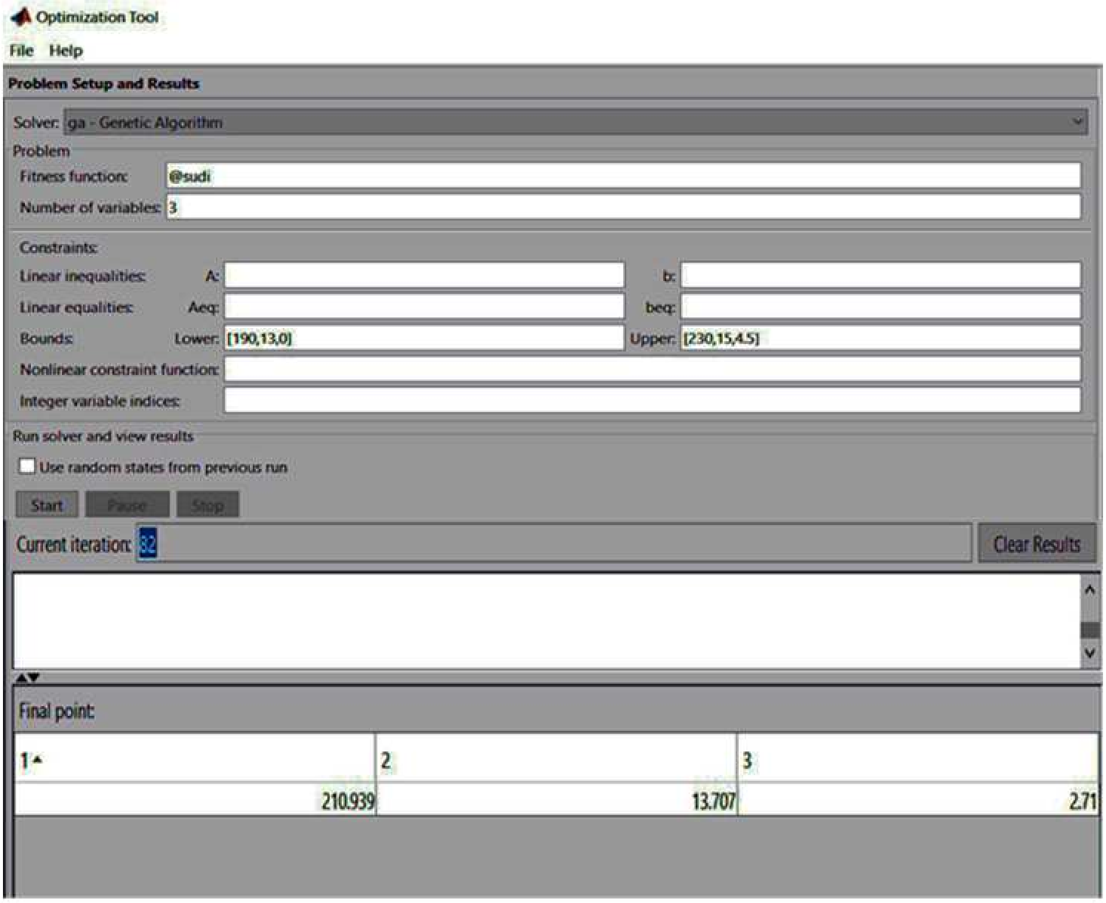


Figure 23: Genetic Algorithm Output.

4. CONCLUSIONS

The new filler wire developed with both magnesium and silicon content can be used successfully for welding 6082 aluminium alloys. From the present investigation it is clear that the addition of magnesium up to 2.71% by weight to ER4043 filler wire can substantially improve the mechanical properties of the welded joint. This improvement is due to the formation of magnesium silicide intermetallic phase in the weld zone. Filler wire chemical composition has a significant role in the strength of the welded joint. Further research will be useful for developing superior quality filler wire which can impart better mechanical properties for the welded joint of this aluminium alloy.

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